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Technical Report

Fifth Progress Report: Development of an HY-130/150 Weldment

Applied Research Laboratory
United States Steel
Monroeville, Pennsylvania

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FIFTH PROGRESS REPORT: DEVELOPMENT OF AN HY-130/150 WELDMENT
(40.018-001)(38)(a-ORD-NP-3)(S-10000-5)

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Approved by J. H. Gross, Division Chief

Abstract

At the end of the fourth report period (June 30, 1964), work on Bureau of Ships Contract No. NObs-88540, SR007-01-01, Task 853, to develop a submarine-hull weldment with a yield strength in the range 130 to 150 ksi indicated that a steel (5Ni-Cr-Mo-V) meeting most of the requirements had been developed but that improvements in a compatible filler metal were required. Therefore, filler-metal studies were to be accelerated.

During the fifth report period (July 1 to October 31, 1964) base-metal studies have been concentrated on mill practices for producing the 5Ni-Cr-Mo-V steel, on final composition-adjustment studies, and on an evaluation of forgings and castings produced from the 5Ni-Cr-Mo-V steel. Preliminary results of these studies have all been encouraging and the studies are being continued. However, a recent Bureau of Ships decision to increase the thickness requirements for an HY-130/150 weldment may require additional base-metal-composition development work.

Significant improvements in the strength and toughness of experimental MIG filler metals have been observed in recent studies. However, many additional experimental MIG and covered-electrode filler metals are still being evaluated. Therefore, the selection of an optimum filler metal has been deferred pending completion of these studies. Consequently, the initiation of the weldment-evaluation program has also been postponed until about January 1965.

Initial low-cycle-fatigue and corrosion studies comparing the 5Ni-Cr-Mo-V steel with HY-80 steel were extremely encouraging. Plates of the 5Ni-Cr-Mo-V steel up to 3-3/8 inches thick were cold-formed in a shipyard and the results of the study showed that the 5Ni-Cr-Mo-V steel readily meets the forming requirements.

Every effort is being made to complete the work required to meet the previously projected schedule and to provide the materials for the fabrication of a prototype structure during the third quarter of 1965.

Introduction

During the period July 1 to October 31, 1964, work has continued on Bureau of Ships Contract No. NObs-88540, SR-007-01-01, Task 853, to develop a submarine-hull weldment with a yield strength in the range 130 to 150 ksi (HY-130/150). The status of the program as of June 30, 1964, including work in progress, was summarized in the fourth quarterly report.[1)*] Most of the studies that were in progress at that time have been completed or significantly advanced during the fifth report period. The detailed results of these studies have been described in individual reports, which are summarized in the present report. In addition, the present report describes the activities that are currently in progress or planned for the immediate future.

BASE-METAL DEVELOPMENT

During the past report period, work has been completed and reported on (1) the effect of tempering and stress relieving on the properties of 5Ni-Cr-Mo-V steel, (2) the effect of cross-rolling ratio on the anisotropy of 5Ni-Cr-Mo-V steel plates, and (3) an evaluation of HP-150 steel. Work described in the fourth quarterly report[1)] on composition adjustments, melting practices, and evaluations of forgings and castings is still in progress. In addition, as a part of the composition-adjustment studies, Laboratory studies have been initiated to determine the effect of

*See References.

composition on the susceptibility of 5Ni-Cr-Mo-V steel to embrittlement during tempering and during stress relieving and to determine the effect of variation in sulfur content on the mechanical properties of the 5Ni-Cr-Mo-V steel. Finally, a number of miscellaneous mechanical and physical properties of the 5Ni-Cr-Mo-V steel have been determined, and a program has been planned to investigate the properties of the 5Ni-Cr-Mo-V steel in 6-inch-thick plates.

Work Completed

Effect of Tempering and Stress-Relieving Treatments on the Mechanical Properties of HY-80 and 5Ni-Cr-Mo-V Production Steels[2)]

Although most plates for submarine hulls are not normally stress-relieved, highly deformed hull plates are stress-relieved, and plates for other applications may require stress relieving. Therefore, a study was initiated to determine the effect of stress relieving for times up to 125 hours in the temperature range 950 to 1050 F on the properties of quenched and tempered plates of the 5Ni-Cr-Mo-V experimental HY-130/150 steel. In addition, the effect of tempering for similar times and temperatures on the properties of quenched plates was determined. For comparison, similar studies were conducted on an open-hearth and on an electric-furnace HY-80 steel.

The tempering study showed that the 5Ni-Cr-Mo-V steel was more resistant to softening during long-time tempering than the HY-80 steels and

that its Charpy V-notch energy absorption in the yield-strength range 130 to 150 ksi was higher than those of the HY-80 steels. However, the 5Ni-Cr-Mo-V steel was more susceptible to temper embrittlement than the HY-80 steels.

The stress-relieving study showed that the yield strength of quenched and tempered HY-80 steels (about 90 ksi) was not significantly changed by stress relieving the steels for times up to 125 hours at temperatures of 950 to 1050 F. The yield strength of quenched and tempered 5Ni-Cr-Mo-V steel (about 145 ksi) was not significantly affected by similar stress-relieving treatments except that stress relieving at the highest temperature (1050 F) and longest time (125 hours) did lower the yield strength about 25 ksi.

The transition temperature of the HY-80 and the 5Ni-Cr-Mo-V steels was raised by the stress-relieving treatments, particularly by the 125-hour treatment followed by slow cooling. However, the transition temperature of the HY-80 steels was not raised enough to affect the energy absorption at 0 F, whereas the transition temperature of the 5Ni-Cr-Mo-V steel was raised enough to lower the energy absorption at 0 F. The effect of stress relieving on transition curves for the 5Ni-Cr-Mo-V steel is shown in Figure 1.

The stress-relief embrittlement of the 5Ni-Cr-Mo-V steel does not appear to be a serious problem except in very heavy plates that would be stress-relieved many times, a practice that is not common. Studies are now

in progress to determine whether minor composition changes can reduce the susceptibility of the 5Ni-Cr-Mo-V steel to temper embrittlement.

Effect of Rolling Ratio on the Anisotropy of 5Ni-Cr-Mo-V Steel Plates[3)]

For many applications, the mechanical properties of plate steels are specified in the direction of minimum rolling (weak direction) as well as in the direction of maximum rolling (strong direction). Such a requirement is specified (MIL-S-16216G) for HY-80 steel, the current submarine-hull steel. Therefore, a study was initiated to evaluate the effect of rolling ratio (from straightaway rolling to 1 to 1 cross rolling) on the anisotropy of 1-inch-thick plates (rolled in the Laboratory from 7-1/4-inch-thick slabs) of the 5Ni-Cr-Mo-V experimental HY-130/150 steel and the effect of subsequent heat treatments on this anisotropy.

The results showed that the tensile properties of the as-rolled plates were not significantly affected by the amount of cross rolling except that the reduction of area was slightly higher in the strong direction than in the weak direction for cross-rolling ratios of 8 to 1 and higher. At cross-rolling ratios of 4 to 1 and lower, the plates exhibited no significant anisotropy in the Charpy V-notch energy absorption at 0 F. However, at cross-rolling ratios of 8 to 1 and higher, the energy absorption in the strong direction was 40 to 58 ft-lb higher than that in the weak direction. As shown in Figure 2 the energy-absorption anisotropy of the as-rolled plates

was reduced by the standard austenitizing, quenching, and tempering treatment, and it was further reduced by a double-austenitizing treatment.

The results summarized in Figure 2 generally indicate that 5Ni-Cr-Mo-V steel plates should not exhibit any deleterious anisotropy if the rolling ratios are 4 to 1 or lower for single-austenitized plates or 8 to 1 or lower for double-austenitized plates.

An Evaluation of HP-150 Steel[4)]

Republic Steel Corporation has proposed a 3Ni-Cr-Mo steel (HP-150) having a minimum yield strength of 150 ksi and good notch toughness for heavy plates, structural sections, and forgings. Preliminary investigations by the Navy indicated that the HP-150 steel might be promising as an HY-130/150 submarine-hull steel, and therefore the Applied Research Laboratory evaluated the mechanical properties, temperability, hardenability, and welding characteristics of plate samples of HP-150 steel that were obtained from the Bureau of Ships Applied Science Laboratory.

Base-metal evaluation of 2-inch-thick plates of HP-150 steel indicated that the as-received mechanical properties were quite good and were similar to those of 2-inch-thick production plates of 5Ni-Cr-Mo-V steel, the steel currently being extensively evaluated by the Applied Research Laboratory as a possible HY-130/150 steel. Base-metal evaluations also indicated that the hardenability of the HP-150 steel is adequate for 4-inch-thick plate. However, results of a tempering study showed that the

temperability of the HP-150 steel may not be satisfactory at yield strengths below 160 ksi.

A weldability evaluation indicated that the weld-heat-affected-zone toughness of the HP-150 steel in the peak-temperature region 1400 to 2400 F (18 to 37 ft-lb at 0 F) was poor compared with that of the 5Ni-Cr-Mo-V steel (82 to 94 ft-lb at 0 F). The difference in the heat-affected-zone toughness between the two steels is apparently related to the differences in the heat-affected-zone hardness and in the carbon content of the HP-150 and 5Ni-Cr-Mo-V steels (48 R_C and 0.26% C and 38 R_C and 0.11% C, respectively). Results of restraint-cracking tests with both covered electrode and MIG welding processes indicated that the weld-heat-affected-zone crack susceptibility of the HP-150 steel is high compared with that of HY-80 and 5Ni-Cr-Mo-V steels, even in specimens welded with a 200 F preheat and interpass temperature.

In general, the evaluation of the HP-150 steel samples indicated that the mechanical properties and hardenability of the HP-150 steel are similar to those of the 5Ni-Cr-Mo-V steel, but that the temperability and weldability of the HP-150 steel are distinctly poorer than those of the 5Ni-Cr-Mo-V steel. Therefore, no additional studies of the HP-150 steel are planned.

Work In Progress

Composition-Adjustment Studies

Mechanical properties are now being obtained on the 30-heat statistically designed program described in the fourth quarterly progress report[1)] to determine the effect of variation in manganese, nickel, chromium, molybdenum, and vanadium on the properties of the 5Ni-Cr-Mo-V steel, and results will be reported during the next quarter. In addition, some of the plate material from each of the above 30 heats will be stress relieved for long times (up to 125 hours) at 1000 F to evaluate the effects of variation in composition on the tendency of the 5Ni-Cr-Mo-V steel to be embrittled during stress relieving. Six additional heats that include variations in phosphorus and substitution of columbium for vanadium will also be included in this stress-relieving study.

Although a large amount of data are available to show the detrimental effect of increasing sulfur content on the Charpy V-notch shear energy of high-yield-strength quenched and tempered steels, including data from a Laboratory study on the 7½Ni-Cr-Mo steel, the effect of sulfur content on the 5Ni-Cr-Mo-V steel has not been systematically studied. Therefore, a study has been initiated to determine the effect of increasing the sulfur content from 0.002 to 0.022 percent in increments of 0.004 percent on the notch toughness of the 5Ni-Cr-Mo-V steel. Six 100-pound vacuum-melted and vacuum-poured steels will be evaluated and the possible influence of air melting will be determined by

evaluating 100-pound air-melted heats at the extremes of sulfur content (0.002% and 0.022% sulfur).

Melting-Practice Studies

Electric-Furnace Practice. A third 80-ton electric-furnace heat (No. X53957) of 5Ni-Cr-Mo-V steel was produced on September 29, 1964. Material from this heat and from the second 80-ton heat (heat No. X53588) will be used in the weldment-evaluation program that has been planned in conjunction with the various Naval laboratories. The chemical composition of heat No. X53957 and the mechanical properties of some of the plates from this heat are shown in Table I. Data on all plates are not available because the evaluation of the heat is still in progress; however, preliminary results indicate that the strength-toughness properties are again excellent.

Basic-Oxygen-Steelmaking Process. Evaluation of the initial 40-ton basic-oxygen-steelmaking heat (heat No. 6Z1237) described in the fourth quarterly report indicated the plate product had poor notch toughness because of the presence o sulfide stringers. A careful assessment of the steel and the steelmaking practice has led to the conclusion that minor changes in deoxidation practice should eliminate the sulfide stringers and markedly improve the notch toughness of the steel. Additional 40-ton basic-oxygen-steelmaking heats have been planned so that the proposed revised deoxidation practices may be investigated.

Vacuum-Consumable-Electrode Remelting. The 28-inch-diameter, 24,000-pound ingot from heat No. 6Z1237 has been vacuum-consumable-electrode

remelted, and upset-forged to three slabs. The slabs are now ready for rolling to 1/2-, 1-, and 2-inch-thick plates. After rolling the plates will be inspected, heat treated, and evaluated.

Evaluation of Forgings, Castings, and Structural Shapes

Production of a Sample Forging. The ring forging described in the fourth quarterly progress report[1)] was successfully produced. Ultrasonic testing indicated that the forging was free from defects. Heat treatment has now been completed and the forged ring is being sectioned in preparation for the extensive evaluation of the mechanical properties described in the fourth quarterly report.

Production of Sample Castings. Four 50-pound (1- by 6- by 6-inch) and three 500-pound (4- by 12- by 12-inch) plate castings have been produced from Laboratory air-induction-melted heats. Evaluation of two of the 1-inch-thick plate castings and one of the 4-inch-thick plate castings has been completed. The compositions and mechanical properties of these castings are shown in Table II. The yield strength and notch toughness of the 4-inch-thick casting (about 147 ksi yield strength and 70 ft-lb Charpy V-notch energy absorption at 0 F) was satisfactory, but the notch toughness of the 1-inch-thick casting (about 42 ft-lb Charpy V-notch energy absorption at 0 F at a yield strength of 151 ksi) was lower than desired. The higher carbon content (0.15%) and the greater difficulty in feeding the 1-inch-thick casting are probably responsible for the lower notch toughness. Macroetch

sections of the remaining four castings (made with modifications in phosphorus and silicon content) indicate that they are sound. Mechanical properties are now being determined on the latter castings.

Production of Structural Shapes. Wide-flange structural shapes have been produced without difficulty from the third electric-furnace heat of 5Ni-Cr-Mo-V steel (heat No. X53957). The shape, a CB103 section, weighs 112 pounds per foot, has a 3/4-inch-thick web, a 1-1/4-inch-thick flange, and is 11-3/8 inches deep and 10-3/8 inches wide. Preliminary evaluation of the mechanical properties of the CB103 sections indicates that very good notch toughness (on the order of 100 ft-lb Charpy V-notch energy at 0 F) was achieved both in the longitudinal and transverse direction.

Miscellaneous Mechanical and Physical Properties

Specific data are occasionally needed on certain physical and mechanical properties of the 5Ni-Cr-Mo-V steel that would not be obtained during the usual evaluation. Information of this type that has been accumulated is presented in Table III. Included in Table III are the critical temperatures for the steel, recommended heat treatment, modulus of elasticity, coefficient of linear expansion, density, magnetic properties, machinability, and elevated-temperature tensile properties.

Work Planned

As part of the study of melting practices, it may be advisable to produce additional electric-furnace heats of the 5Ni-Cr-Mo-V steel that may

incorporate vacuum degassing and/or vacuum-carbon deoxidation. It may also be desirable to produce a second forging and to obtain a sample casting from a steel foundry.

On November 6, 1964, U. S. Steel was advised by the Bureau of Ships (Codes 634 B and 442) that recent design studies indicated that the average thickness of an HY-130/150 steel plate would be 3 inches rather than 2 inches and that the maximum thickness would be about 6 inches rather than 4 inches. The importance of these changes in the plate-thickness requirements will be immediately assessed and appropriate investigative programs initiated.

JOINING DEVELOPMENT

During the past report period work has been completed on (1) a final statistical program on weld-heat-affected-zone cracking of Ni-Cr-Mo steels, (2) a study of the effects of composition on the properties of inert-gas-shielded metal-arc (MIG) filler metals, (3) a third study of the effects of composition and coating formulation on the properties of covered-electrode weld metals, and (4) additional work on the all-position interrupted-arc welding process. In addition, considerable progress was made on (1) a statistical program to determine the effects of carbon, manganese, nickel, chromium, and vanadium on 5Ni-Cr-Mo-V filler metals and (2) a study of the effects of filler-metal melting process and MIG welding technique on the properties of 2Mn-2Ni-Cr-Mo filler metals. During the past report

period, a third MIG-major-element study was initiated to determine the properties of Mn-Ni-Cr-Mo-(V) filler metals with compositions outside the range previously investigated.

Work Completed

Base-Metal Weldability

Effects of Composition on Heat-Affected-Zone Cracking of Ni-Cr-Mo Steel Weldments—II.[5] Welding studies associated with the development of an HY-130/150 submarine-hull steel were designed to define the composition limits within which Ni-Cr-Mo steels will exhibit a minimum susceptibility to weld-heat-affected-zone cracking. The studies comprised two statistically designed experiments. The results of the first experiment, which was previously reported, in which the effects of carbon (0.05 to 0.21%), manganese (0.30 to 1.50%), phosphorus (0.003 to 0.027%), sulfur (0.003 to 0.027%), and nickel (1.00 to 9.00%) were studied, indicated that increased carbon, manganese, and nickel contents increased crack susceptibility but that increased phosphorus and sulfur contents did not. A second statistical program was undertaken to determine the effects of carbon (0.10 to 0.20%), manganese (0.50 to 1.30%), chromium (0.60 to 2.00%), molybdenum (0.30 to 0.90%), and vanadium (residual to 0.07%) on weld-heat-affected-zone cracking in cruciform tests of 22 statistically selected 5Ni-Cr-Mo steels. The statistical design and experimental procedure were the same as those used in the first study so that the results could be jointly analyzed.

The results of the second study indicated that an increase in carbon content strongly increased crack susceptibility, an increase in manganese and chromium moderately increased crack susceptibility, but that an increase in molybdenum and vanadium contents did not significantly influence crack susceptibility. An analysis of the data from the present study combined with the data from the first study resulted in the following final prediction equation:

$$\text{Cruciform Cracking, \%} = -105 + (499 \pm 45)(\%C) + (23.8 \pm 5.4)(\%Mn) + (7.54 \pm 1.23)(\%Ni) + (15.0 \pm 4.3)(\%Cr)$$

By using the prediction equation for cracking and a hardenability equation, the composition limits were calculated for minimum crack susceptibility and adequate hardenability ($D_I = 15$) in the heat-affected zone of an 0.10C-0.5Mo-0.07V steel. The limits ranged from 0.7 Mn, 4.0 Ni, 1.1 Cr to 0.55 Mn, 5.0 Ni, 0.9 Cr. These composition limits were subsequently used in the design of the 5Ni-Cr-Mo-V steel currently being extensively evaluated for the HY-130/150 steel application.

Filler-Metal and Joining-Technique Development

MIG-Major-Element Study.[6)] Nineteen 2Mn-2Ni-Cr-Mo filler metals were deposited in buttered joints with a preheat and interpass temperature in the range 200 to 225 F. In general, the results of mechanical-property tests on the undiluted weld metals, Table IV, indicated that minimum manganese and nickel contents of 2 percent each were necessary to produce a minimum yield strength of 140 ksi. In general, the toughness of the weld

metals was excellent; and the tensile ductility in the absence of flaws was good. As noted in Table IV, three of the six weld metals that exhibited a yield strength over 140 ksi contained transverse weld-metal cracks. Because the present results confirm past observations[7)] that the crack susceptibility of 2Mn-2Ni-Cr-Mo weld metals tends to increase when a preheat temperature is used that will produce a minimum yield strength of 140 ksi, several filler-metal-composition studies (to be described subsequently herein) were recently initiated to determine the properties of Mn-Ni-Cr-Mo-(V) weld metals with compositions outside the range previously investigated. In addition, work has been initiated to determine the effects of AC MIG welding on the properties of 2Mn-2Ni-Cr-Mo weld metals.

Covered-Electrode Filler-Metal Development. To determine the effect of silicon, molybdenum, and vanadium content on the mechanical properties of 2Mn-2Ni-Cr-Mo covered-electrode weld metals, seven experimental AWS Class E XXX18 electrodes were deposited by the same procedures used in previous covered-electrode studies.[8)] The results of mechanical-property tests, Table V, indicated that an increase in molybdenum content increased the yield strength slightly and decreased the toughness moderately. An increase in vanadium caused a significant increase in the yield strength and a moderate decrease in the toughness. An increase in silicon did not affect yield strength but did moderately reduce toughness, only at low temperatures. In general, the results indicated that vanadium might be used effectively

to increase weld-metal yield strength provided that the loss in toughness attendant with a vanadium addition could be tolerated. The results also indicated that the silicon content of the weld metal should be maintained at a low level consistent with complete weld-metal deoxidation.

As indicated in the fourth quarterly report,[1] one of twelve experimental coating formulations investigated showed promise in that weld metal deposited from this electrode was tougher than weld metal deposited from an electrode coated with the standard formulation. This experimental coating contained no ferrotitanium. Recently, an additional coating-formulation study was completed, and the results indicated that the elimination of ferrotitanium did not produce an increase in toughness, but that a large ferrotitanium addition did significantly decrease toughness. The details of all the coating-formulation work performed to date have been summarized in a recent report.[9]

<u>MIG-All-Position Procedures</u>. Additional work was recently completed on the effects of (1) contact-tube-to-work distance, (2) power-supply characteristics, and (3) electrode diameter on the all-position operability of the interrupted-arc welding process. In general, the results showed that within a practical range of contact-tube-to-work distance, the penetration could be changed about 20 percent. In addition, the results showed that the use of an 0.045-inch-diameter electrode in combination with a slightly rising power-supply characteristic produced the best all-position operability. The

MIG-Major-Element Study. A study has been initiated to determine the effects of manganese (0.75 to 2.15%), nickel (2.0 to 5.0%), chromium (0.55 to 1.0%), and vanadium (0.0 to 0.05%) on the mechanical properties of 35 Mn-Ni-Cr-Mo-(V) filler metals deposited by the MIG welding process. The 35 filler metals have been melted and rolled to rod, and 18 of the 35 have been drawn to welding wire. All these filler metals will be evaluated in weldments made with 5Ni-Cr-Mo-V base plate within the next report period.

Covered-Electrode Filler-Metal Study. A series of 26 experimental covered electrodes are currently being evaluated by depositing each filler metal in a 5Ni-Cr-Mo-V joint at two different preheat levels (200 F and 300 F). The compositions being investigated include some that exhibited good properties in previous investigations, as well as new compositions that might be more compatible with the 5Ni-Cr-Mo-V base plate. The effects of (1) lower welding current, (2) small-diameter electrodes, and (3) alternating welding current on weld-metal mechanical properties are also being evaluated in this study.

MIG-Filler-Metal Processing and Joining-Technique Study. A study of the effects of filler-metal melting process, deoxidation practice, and welding technique on the mechanical properties of undiluted 2Mn-2Ni-Cr-Mo weld metals is nearly completed, and the results will be reported in the next progress report.

MIG-All-Position Procedures. Filler metals are currently being deposited in 5Ni-Cr-Mo-V joints by the interrupted-arc process. The effects of process parameters on weld-metal mechanical properties are being determined by using the optimum conditions established in previous investigations.[10)]

Work Planned

Until several of the studies currently in progress are completed, no new programs will be initiated for the forthcoming report period.

STRUCTURAL EVALUATION

During the past report period, plates were cold-formed under actual submarine-yard conditions to verify the Laboratory formability predictions previously established for the 5Ni-Cr-Mo-V steel. Initial results on welded fatigue specimens were obtained, and corrosion fatigue tests have been initiated. The electrochemical properties of the 5Ni-Cr-Mo-V steel have been determined, and the results of 6-month sea-water-exposure tests of the 5Ni-Cr-Mo-V steels and weldments have been compared with similar results for the HY-80 steels and weldments.

Work Completed

Low-Cycle Fatigue of Experimental HY-130/150 and HY-180/210 Steels and Weldments[11)]

Because submarine hulls are cyclically loaded at high stresses, the fatigue behavior of experimental submarine-hull steels is important in

evaluating their structural suitability. Therefore, the Applied Research Laboratory determined the low-cycle high-strain fatigue properties of the 5Ni-Cr-Mo-V experimental HY-130/150 steel, the 12Ni-5Cr-3Mo experimental HY-180/210 steel, and HY-80 steel, the current submarine-hull steel. In addition, the fatigue behavior of weldments of the 5Ni-Cr-Mo-V and HY-80 steels was determined, and the fatigue data for the unwelded specimens were analyzed in terms of recent theories proposed by Langer[11)], by Manson[11)], and by Morrow[11)] for predicting low-cycle fatigue behavior.

The results, Table VI and Figure 3, showed that in the cycle-life range of primary interest (10^4 to 10^5 cycles), the fatigue strength (strain range to cause failure) of the 5Ni-Cr-Mo-V and 12Ni-5Cr-3Mo steels was significantly higher than that of HY-80 steel. However, to insure a corresponding resistance to failure by fatigue, the fatigue strength of submarine-hull materials should be proportional to the yield strength of the material. On this basis, the fatigue strength of the 5Ni-Cr-Mo-V steel is slightly lower than thatof HY-80 steel at a life of 10,000 cycles and essentially the same at 100,000 cycles, whereas the fatigue strength of the 12Ni-5Cr-3Mo steel is lower than that of HY-80 steel at all cycle lives. On the same yield-strength basis, the 5Ni-Cr-Mo-V steel covered-electrode weldments had a fatigue strength at 10,000 cycles slightly lower and a fatigue strength at 100,000 cycles slightly higher than that of the HY-80 steel covered-electrode weldments. The fatigue strength of the 5Ni-Cr-Mo-V steel MIG weldments was

superior to that of the HY-80 steel covered-electrode weldments at 10,000 and 100,000 cycles.

The fatigue analysis proposed by Morrow agrees better with the experimental values than the analysis proposed by Langer and by Manson because Morrow's predictory equations are based on experimental fatigue data, whereas Langer and Manson predict fatigue performance from tensile properties.

The results indicate that in the cycle range of primary interest, the fatigue properties of the 5Ni-Cr-Mo-V steel and weldments are surprisingly good and should permit design on the same yield-strength basis as that currently employed for HY-80 steel and weldments.

Rotating-Beam Fatigue Studies of Experimental HY-130/150 and HY-180/210 Steels[12)]

Because submarines are repeatedly pressurized during service, the high-stress, low-cycle fatigue strength of pressure-hull materials is an important property. Therefore, a study was initiated to obtain a preliminary assessment of the fatigue strength of four experimental HY-130/150 steels, including the promising 5Ni-Cr-Mo-V steel, and of one experimental HY-180/210 steel, for comparison with the fatigue strength of HY-80 steel.

The results of rotating-beam fatigue tests conducted at 0.8 tensile strength on smooth specimens in air showed that the fatigue and tensile strengths of the 5Ni-Cr-Mo-V steel were 40 to 45 percent greater than those

of the HY-80 steel. Similar tests on smooth specimens in synthetic sea water and on notched specimens in air and in synthetic sea water indicated that all three conditions lowered the fatigue strength of all steels tested, and that the notched specimen tested in synthetic sea water showed the greatest loss in fatigue strength. Although the 5Ni-Cr-Mo-V experimental HY-130/150 steel showed a slightly greater sensitivity to notches and a sea-water environment than the HY-80 steel when tested at the same percentage of tensile strength, the differences were not statistically significant.

Thus, the results of a preliminary fatigue study indicate that high-stress, low-cycle fatigue strength should not be a greater limiting factor in the design of HY-130/150 submarine hulls than in the design of the present HY-80 submarine hulls.

Electrochemical Behavior of Experimental Submarine-Hull Steels in Synthetic Sea Water[13)]

Corrosion studies were conducted to determine the electrochemical properties of weldments of two 5Ni-Cr-Mo-V steels and HY-80 steel in synthetic sea water.

The results of Laboratory tests, Figure 4, showed that there was no significant difference in corrosion potential among the base metals. The difference in corrosion potential between base metal and weld metal was much less for the 5Ni-Cr-Mo-V steel weldments (experimental MIG filler metal R9376-B) than for the HY-80 weldments (E11018 filler metal). The cathodic

polarization behavior of the base metals, weld metals, and weldments was essentially the same. After 124 hours of exposure, galvanic corrosion of weld metals coupled to base metals was much less for the 5Ni-Cr-Mo-V steel weldments than for the HY-80 steel weldments.

The above results have been confirmed by the results of corrosion tests conducted at Wrightsville Beach, North Carolina, in flowing and non-flowing sea water with welded and unwelded samples of HY-80 steel and 5Ni-Cr-Mo-V steel. With HY-80 steel, the weld metal corroded about twice as fast as the base metal. No galvanic effects, however, were noted between weld metal and base metal for the 5Ni-Cr-Mo-V steel weldments. Thus (for the filler metal investigated) it appears that the corrosion performance of the 5Ni-Cr-Mo-V steel weldments should be better than that of the presently used HY-80 steel weldments.

Work In Progress

Strength and Formability

Previous results of a Laboratory formability study[14)] indicated that the 5Ni-Cr-Mo-V steel could be cold-formed readily to extremely small radii. Results of Laboratory tests of 1/4-, 3/8-, and 1/2-inch-thick plates cold-formed in plane strain (w/t = 8) are presented in Figure 5 and show that the plates were cold-formed without cracking to radii at least as small as the minimum predicted radii.

Plates 1, 2, and 3-3/8 inches thick (with w/t ratios equal to 8 or more) were shipped to Newport News for cold forming. Plates of all thicknesses were cold press formed to the minimum predicted bend radii without cracking. The results, Table VII, show that the 5Ni-Cr-Mo-V steel can be formed to the minimum predicted bend radii. As shown in Figure 6, these radii are extremely small, and thus the 5Ni-Cr-Mo-V steel has more than adequate ductility to undergo severe deformation during cold forming.

In addition, two 2-inch-thick plates were cold-formed to various radii to study the effects of cold deformation on the mechanical properties of the 5Ni-Cr-Mo-V steel.

Fracture

Explosion-deformation tests of 5Ni-Cr-Mo-V MIG weldments with the reinforcement ground off and a photogrid applied to the surface to measure deformation characteristics are currently in progress.

Fatigue

Initial results of low-cycle corrosion-fatigue tests, Figure 7, show that the fatigue lives of the 5Ni-Cr-Mo-V steel tested in synthetic sea-water are lower than the fatigue lives of the 5Ni-Cr-Mo-V steel tested in air by about the same amount as the difference in the fatigue lives of the HY-100 steel tested in synthetic sea-water and in air.[5)]

Corrosion

Results of six- and twelve-month sea-water tests at Wrightsville Beach, North Carolina, on HY-80 and 5Ni-Cr-Mo-V steels may be summarized as

follows:

1. Corrosion rates for HY-80 steel, ranging around 5 mpy (mils per year), were about the same as those published in the literature for structural carbon steels.

2. Corrosion rates for the 5Ni-Cr-Mo-V steels were somewhat less than those for the HY-80 steel.

3. The heat-affected zone of the HY-80 steel weldments appeared to be cathodic to both the base metal and weld metal. After one year, the corrosion rate of the weld metal averaged about 5 mpy more than that of the base metal.

4. There was no evidence of any galvanic corrosion of the 5Ni-Cr-Mo-V steels after six months.

These initial results generally confirm the results of the investigation[13)] of electrochemical properties previously discussed.

Work Planned

In addition to continuing existing programs, the effects of cold forming on the mechanical properties of 5Ni-Cr-Mo-V steel will be determined during the next report period.

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6. K. E. Dorschu, "Development of HY-130/150 MIG Weld Metals: Part I," Air Reduction Sales Company Report P&EDD-64-226, November 20, 1964.

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11. S. T. Rolfe, R. P. Haak, and E. J. Imhof, Jr., "Low-Cycle Fatigue of Experimental HY-130/150 and HY-180/210 Steels and Weldments," Applied Research Laboratory Report, Project No. 40.018-001(37), (S-13307, S-13308, and S-23308), December 1, 1964.

12. R. P. Haak, A. W. Loginow, and S. T. Rolfe, "Rotating-Beam Fatigue Studies of Experimental HY-130/150 and HY-180/210 Steels," Applied Research Laboratory Report, Project No. 40.018-001(32), (S-13307 and S-23308), December 1, 1964.

13. E. Williams, "Electrochemical Behavior of Experimental Submarine-Hull Steels in Synthetic Sea Water," Applied Research Laboratory Report, Project No. 40.001-008(1), (S-13303), September 30, 1964.

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15. M. R. Gross, "Low Cycle Fatigue of Materials for Submarine Construction," Naval Engineers Journal, Vol. 75, No. 4, October 1963, p. 783.

Table I

Composition and Mechanical Properties of Third 80-ton Electric-Furnace Heat of 5Ni-Cr-Mo-V Steel (Heat No. X53957)

Average of Two Check Analyses - Percent

C	Mn	P	S	Si	Ni	Cr	Mo	V	Al*	Al**	N	O
0.11	0.78	0.009	0.003	0.23	5.01	0.55	0.55	0.052	0.014	0.019	0.010	0.0026

* Acid soluble
** Total

Typical Mechanical Properties

Plate Thickness, in.	Tempering Temp, F	Specimen Orientation	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation, %	Reduction of Area, %	Charpy V-Notch Energy Absorption, ft-lb +80 F	0 F	-80 F
1/2	1120	Long	144	150	21.0	71.0	95	90	85
		Trans	146	149	19.0	66.8	80	70	63
1	1135	Long	140	147	19.5	68.5	100	98	86
		Trans	141	147	19.0	66.4	82	77	71
1	1070	Long	151	160	18.0	67.4	85	82	75
		Trans	151	160	18.0	63.5	73	68	54
1-1/2	1105	Long	143	149	19.0	64.7	90	86	62
		Trans	143	149	17.5	59.6	65	63	43
2	1105	Long	144	149	18.0	63.7	82	79	52
		Trans	140	149	17.5	61.7	64	63	45

Table II

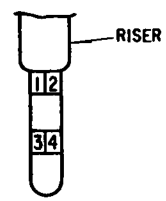
Chemical Composition and Mechanical Properties of 5Ni-Cr-Mo-V Cast Steel Plates

Ladle Analysis, percent

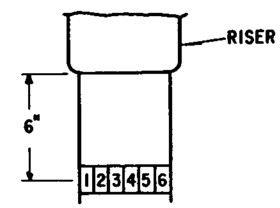
	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al	N
1-Inch-Thick Casting	0.15	0.74	0.001	0.006	0.30	4.93	0.60	0.56	0.07	0.027	0.006
4-Inch-Thick Casting	0.11	0.72	0.002	0.007	0.17	5.03	0.56	0.55	0.06	0.025	0.010

Mechanical Test Specimen Location

At Mid-Length of 1- by 6- by 6-Inch Plate Casting



At Mid-Length of 4- by 12- by 12-Inch Plate Casting



Specimen Location	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	Charpy V-Notch Energy Absorption, at 0 F, ft-lb
1- by 6- by 6-Inch Plate Casting					
1	151	161	16.5	54.8	44
2	151	162	17.0	57.0	46
3	151	161	17.0	55.3	38
4	152	162	17.5	59.3	40
4- by 12- by 12-Inch Plate Casting					
1	147	153	6.0*	12.1*	71
2	147	155	18.0	55.0	73
3	148	154	17.0	52.1	75
4	148	155	17.0	54.0	76
5	147	155	18.0	55.6	66
6	147	154	17.0	58.1	65

*Sand inclusion.

NOTE: Castings were homogenized at 1850 F (1-inch-thick casting) or 1700 F (4-inch-thick casting) and water-quenched. Austenitized at 1500 F, 2 hours, water-quenched. Tempered at 1080 F, 2 hours, water-quenched.

(40.018-001)(38)

Table III

Miscellaneous Mechanical and Physcial Properties of 5Ni-Cr-Mo-V Steel

Critical Temperatures

A_{C1} temperature - 1210 F (for heating rate of 200 F per hour)
A_{C3} temperature - 1415 F (for heating rate of 200 F per hour)
M_s temperature - 715 F

Heat Treatment

Recommended final austenitizing temperature - 1500 F
Recommended tempering temperature range - 1000 to 1150 F
Recommended quenching media - water
Microstructure (as-quenched)
Midthickness up to 2 inches - 100 percent martensite
Midthickness of 4-inch-thick plate - 60 to 75 percent martensite, remainder bainite

Modulus of Elasticity

Tension - 29 x 10^6 psi
Compression - 30 x 10^6 psi

Coefficient of Linear Expansion

80 to 1100 F - 7.1 x 10^{-6} in./in./degree F

Density

30 F - 7.89 g/cc (0.285 lb/cu in.)

(Continued)

Table III (Continued)

Miscellaneous Mechanical and Physical Properties of 5Ni-Cr-Mo-V Steel

Magnetic Properties

B_{sat} (Flux density at saturation) - 20,500 gausses

H_{sat} (Magnetizing force for saturation) - 2200 oersteds

B_r (Residual flux density) (when B_{max} is 15,000 gausses) - 11,000 gausses

H_c (Coercive force) (when B_{max} is 15,000 gausses) - 11.0 oersteds

Permeability (μmax) - 630

Machinability

About the same as for quenched and tempered AISI 4140 steel at 36 R_C

Elevated-Temperature Tensile Properties

Longitudinal Elevated-Temperature Tensile Properties of 1-Inch-Thick Plates

Test Temperature, F	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 2 Inches, %	Reduction of Area, %
80	148	155	19.5	68.1
400	131	143	17.5	59.8
500	132	146	18.0	62.2
600	125	141	19.0	69.4
700	121	136	19.0	71.3
800	113	128	17.5	69.5
900	104	117	17.5	71.1

(40.018-001)(38)

Table IV

Mechanical Properties of Mn-Ni-Cr-Mo MIG Weld Metals

Filler Metal No.	Nominal Composition	Tensile Properties* Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 2 Inches, %	Reduction of Area, %	Charpy V-Notch Impact Properties* Energy Absorption, ft-lb +75 F	+30 F	-60 F
9564	1.85 Mn, 2.00 Ni, 0.70 Cr	135	151	18	64	88	79	47
9656	1.85 Mn, 2.00 Ni, 1.30 Cr	138	156	19	62	97	100	77
9670	1.85 Mn, 2.50 Ni, 1.30 Cr	136	158	12**	22	97	95	82
9562+	2.05 Mn, 1.50 Ni, 1.60 Cr	148	163	18++	58++	ND	58	32
9565	2.05 Mn, 2.00 Ni, 0.60 Cr	138	146	6**	20	106	103	78
9659	2.05 Mn, 2.00 Ni, 0.75 Cr	135	145	20	68	113	105	84
9658	2.05 Mn, 2.00 Ni, 0.90 Cr	137	151	19	65	102	112	70
9563	2.05 Mn, 2.00 Ni, 0.90 Cr-No Ti	128	143	11**	22	91	90	52
9663	2.05 Mn, 2.00 Ni, 0.90 Cr-Low C	119	133	20	70	126	131	94
9669	2.05 Mn, 2.00 Ni, 0.90 Cr-High C	139	159	10**	19	95	97	80
9660	2.05 Mn, 2.00 Ni, 1.05 Cr	144	150	4**	4	104	102	66
9664	2.05 Mn, 2.50 Ni, 0.70 Cr	127	150	18+++	66+++	96	88	37
9665+	2.05 Mn, 2.50 Ni, 1.00 Cr	143	155	6**	15	73	59	21
9568	2.25 Mn, 1.50 Ni, 0.40 Cr	135	147	14**	33	116	106	73
9657	2.25 Mn, 2.00 Ni, 0.70 Cr	132	153	19	65	97	113	83
9661+	2.25 Mn, 2.00 Ni, 1.00 Cr	144	161	9**	22	ND	59	25
9567A	2.25 Mn, 2.50 Ni, 0.60 Cr	141	151	19	68	95	96	82
9667	2.25 Mn, 2.50 Ni, 1.00 Cr	142	154	19+++	64+++	100	97	82
9668	0.75 Mn, 5.00 Ni, 0.55 Cr, 4.0 Co	128	142	15	44	60	60	41

NOTE: All welding wires contained approximately 0.09 C, 0.40 Si, 0.50 Mo, and 0.015 Ti, except as noted. "No Ti" - no Ti added. "Low C" - 0.063 C. "High C" - 0.12 C.

*Average of two tests unless otherwise noted.
**Both tensile fractures contained defects.
+Weld metal contained two transverse cracks.
++Tensile ductility values represent one test specimen only.
+++Tensile ductility reported for one tensile specimen only.

Table V

Mechanical Properties of Experimental Mn-Ni-Cr-Mo Covered-Electrode Weld Metals

Electrode Number	Composition Variable	Tensile Properties* Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 2 Inches, %	Reduction of Area, %	Charpy V-Notch Impact Properties* Energy Absorption, ft-lb +75 F	+30 F	-60 F
AA-095**	Control***	139	155	15	36	42	39	24
AA-315+	0.72 Mo	145	148	5	16	37	30	—
AA-316	0.97 Mo	143	162	11	23	35	28	18
AA-331+	0.07 V	148	160	15	41	35	27	15
AA-330	0.11 V	149	160	16	44	33	26	12
AA-094	0.22 Si	140	154	14	44	46	42	26
AA-329**	0.60 Si	140	157	16	43	40	29	13

*Results are the average of two specimens, except as noted.
**Tensile properties are result of one test.
***The nominal control composition is 0.05 C, 2.0 Mn, 0.014 P, 0.014 S, 0.40 Si, 2.0 Ni, 1.0 Cr, 5.0 Mo, 0.0 V.
+Weld metal contained one or more transverse cracks.

Table VI

Comparative Fatigue Performance for Steels Investigated

Steel	Strain Range to Failure at Indicated Cycles, inches per inch		Ratio of Strain Range to Failure at Indicated Cycles to that for HY-80 Steel, inches per inch	
	10,000	100,000	10,000	100,000
		Unwelded		
HY-80	0.0076	0.0039	---	---
5Ni-Cr-Mo-V	0.0098	0.0061	1.29	1.56
12Ni-5Cr-3Mo	0.0115	0.0070	1.51	1.79

Ratio of yield strength of 5Ni-Cr-Mo-V to HY-80 steels = 1.56
Ratio of yield strength of 12Ni-5Cr-3Mo to HY-80 steels = 2.15

Steel	10,000	100,000	10,000	100,000
		Welded		
HY-80 (Covered electrode)	0.0056	0.0026	---	---
5Ni-Cr-Mo-V (Covered electrode)	0.0061	0.0039	1.09	1.50
5Ni-Cr-Mo-V (MIG)	0.0072	0.0046	1.29	1.77

Ratio of yield strength of 5Ni-Cr-Mo-V weld metal (covered electrode) to that of HY-80 weld metal (covered electrode) = 1.29
Ratio of yield strength of 5Ni-Cr-Mo-V weld metal (MIG) to that of HY-80 weld metal (covered electrode) = 1.23

Table VII

Minimum Predicted Bend Radii for 5Ni-Cr-Mo-V Steel

Plate Thickness, inches	Predicted Minimum Inside Bend Radius, inches	Actual Inside Bend Radius at Cracking, inches
1/4	0.4	Between 0.19 and 0.34
3/8	0.7	Between 0.23 and 0.53
1/2	0.9	Between 0.78 and 0.94
1	1.8	<1.8
1-1/2	2.7	ND*
2	3.6	3.1
2-1/2	4.5	ND
3	5.3	ND
3-3/8	6.1	<5.1
3-1/2	6.2	ND
4	7.1	ND

ND* = not determined.

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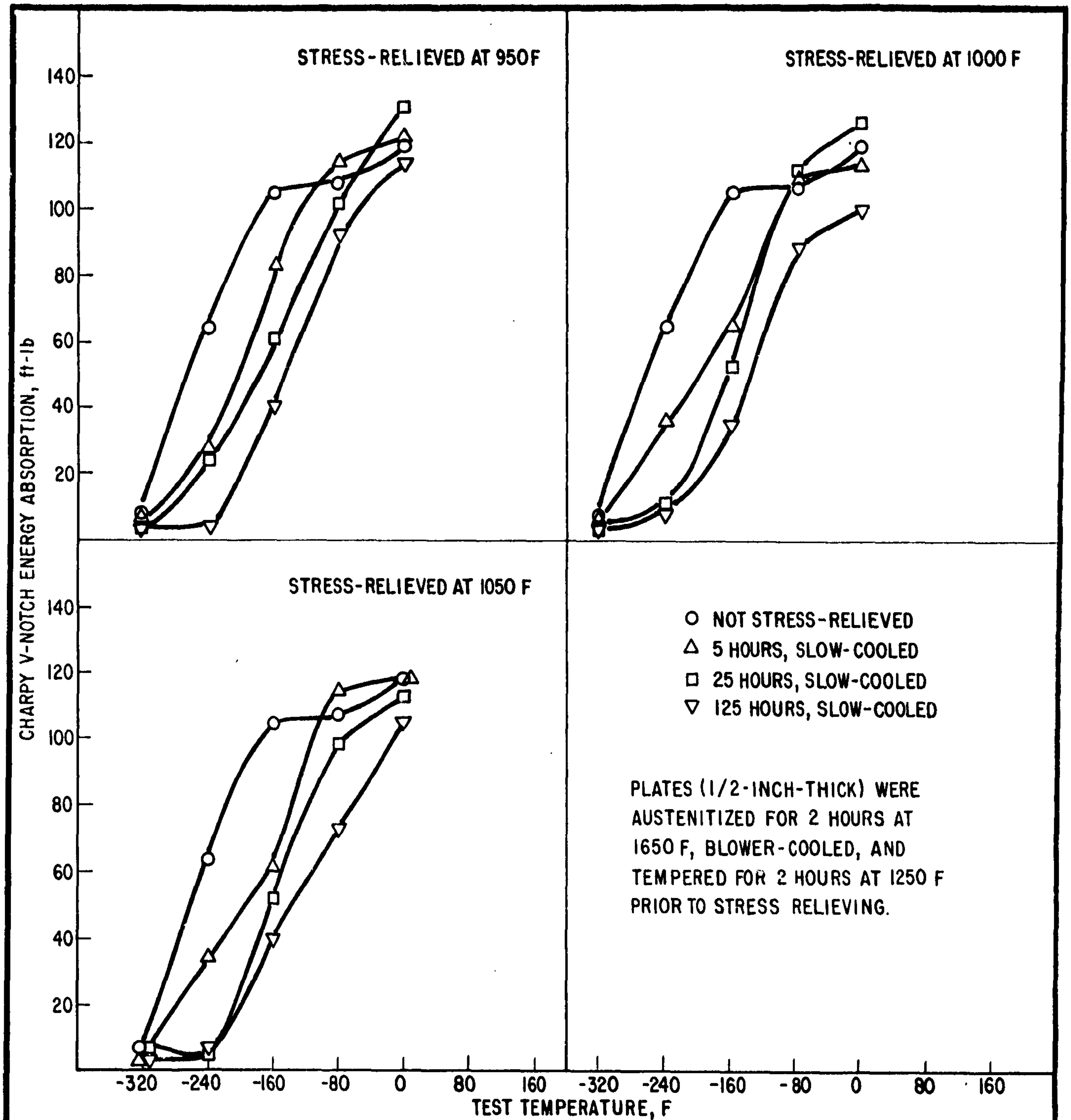

EFFECT OF STRESS-RELIEVING TEMPERATURE AND TIME ON THE ENERGY ABSORPTION OF OPEN-HEARTH HY-80 STEEL (HEAT NO. 72P305)

DRAWN BY M.M.	CHK'D BY S.J.M.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 1
DRAWING No. ARL 18-449		PROJECT No 40.018-001(38) DATE 10/30/64		

ATLAS LITHO CO PGH PA 1035 CLEARPRINT

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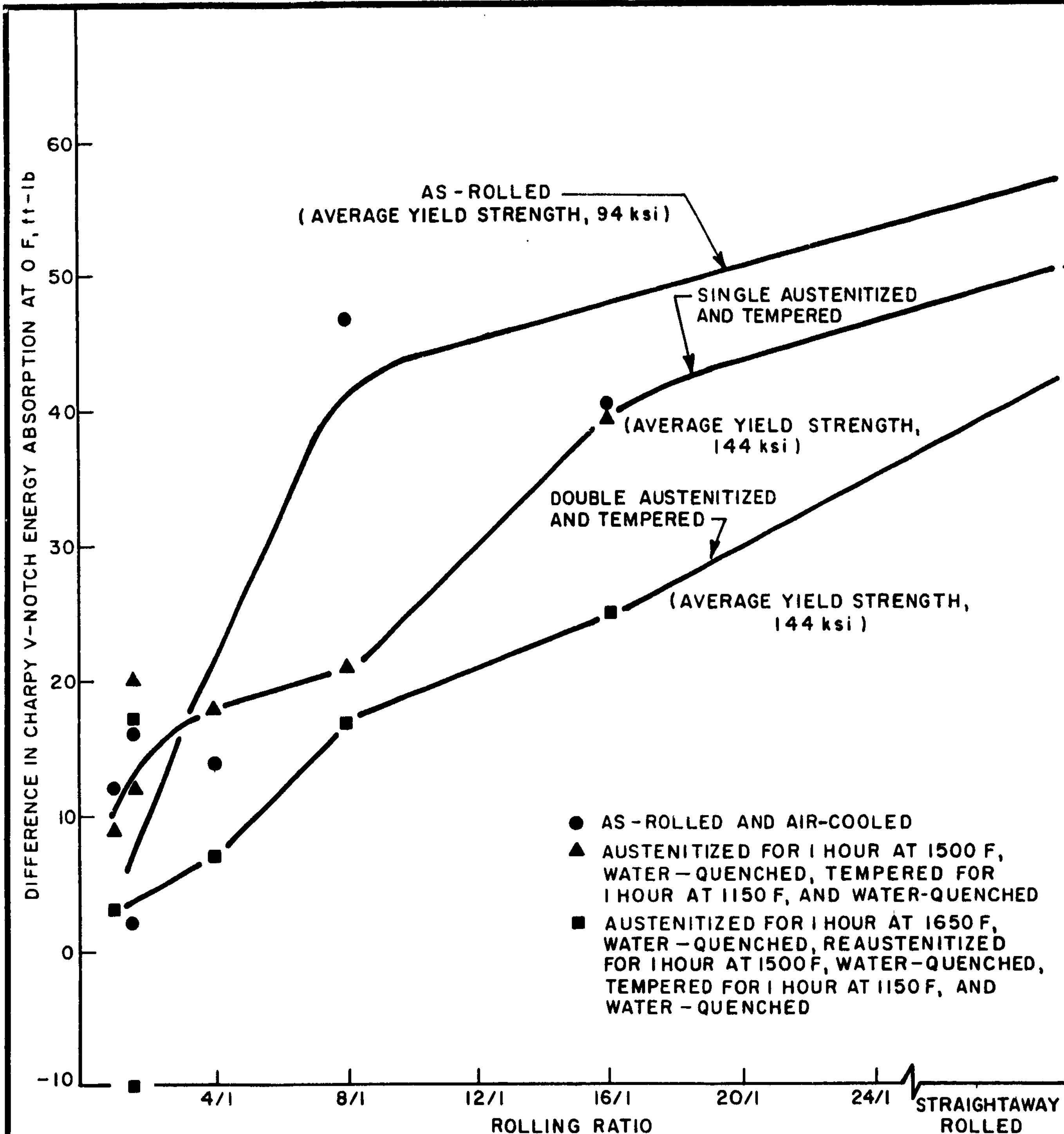
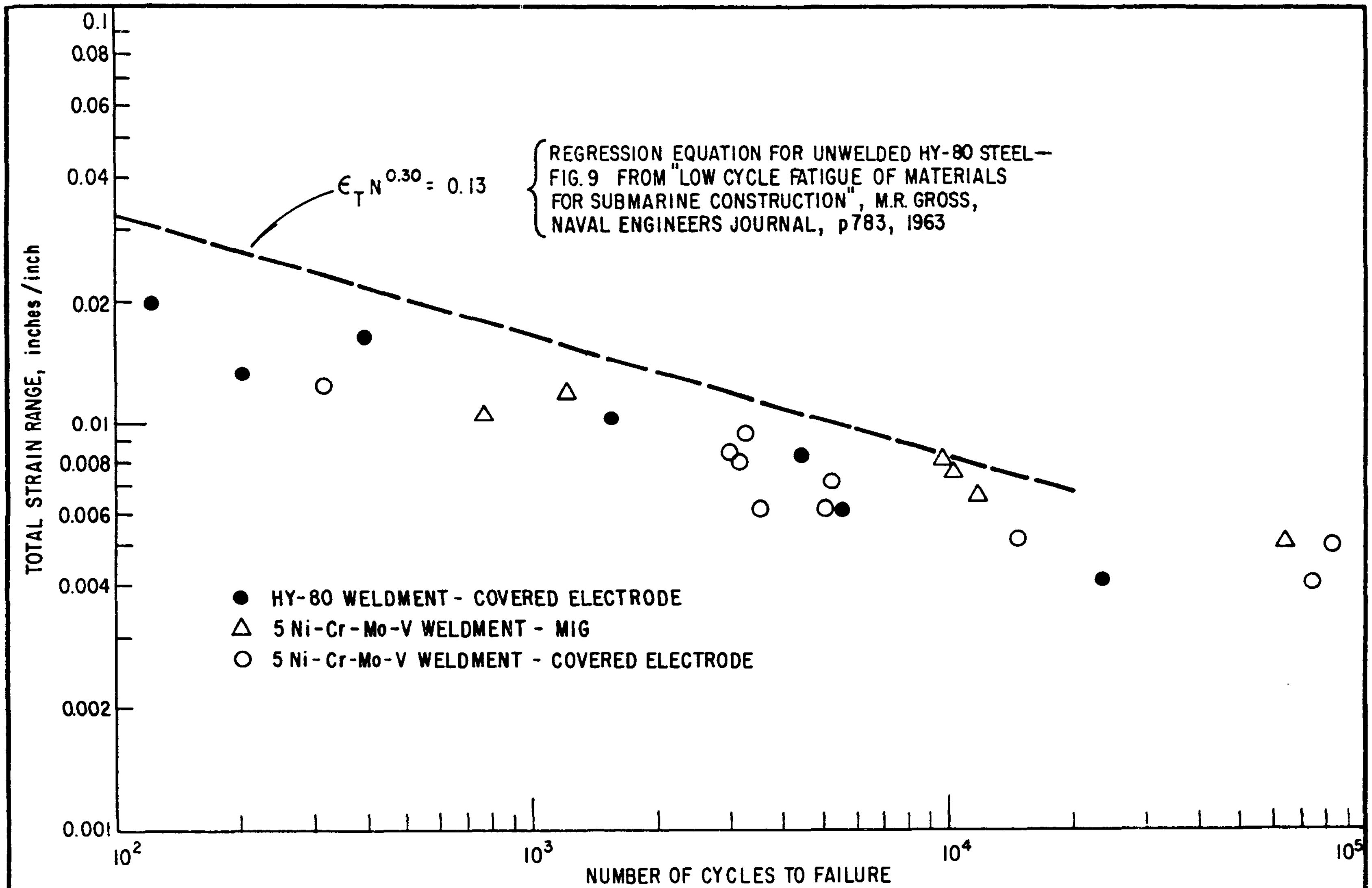


EFFECT OF ROLLING RATIO ON THE CHARPY V-NOTCH ANISOTROPY OF 1-INCH-THICK PLATES OF 5Ni-Cr-Mo-V STEEL

DRAWN BY G.A.Z.	CHK'D BY S.J.M.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 2
DRAWING No. ARL 18-458		PROJECT No 40,018-001 (38) DATE 11-3-64		

ATLAS LITHO CO PGH PA 1028 CLEARPRINT



LOW-CYCLE FATIGUE RESULTS FOR 5 Ni-Cr-Mo-V WELDMENTS AND HY-80 WELDMENTS

DRAWN BY M.M.	CHK'D BY S.T.R.	APPROVED BY J. H. G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 3
DRAWING NO ARL 18-428		PROJECT NO 40.018-001 (38) DATE 11/11/64		

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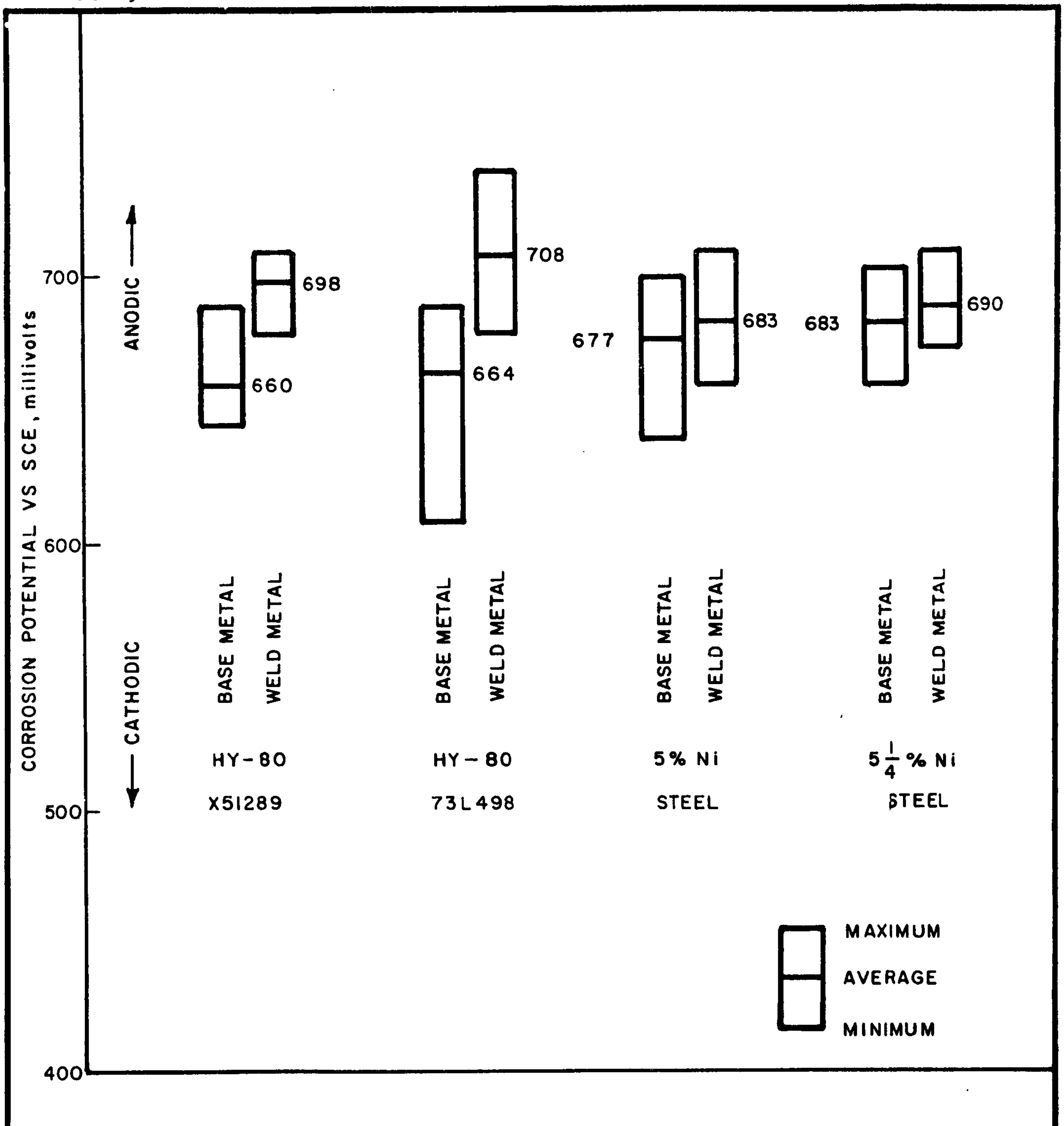


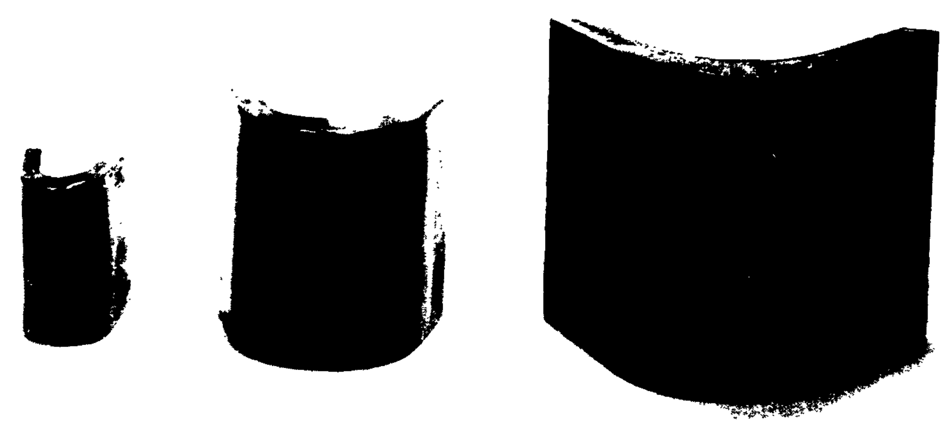
CORROSION POTENTIALS OF HY-80 STEELS AND EXPERIMENTAL SUBMARINE – HULL STEELS IN SYNTHETIC SEA WATER AT ROOM TEMPERATURE

DRAWN BY	CHK'D BY	APPROVED BY	UNITED STATES STEEL CORPORATION	FIGURE NO.
G.A.Z.	E.W.	E.H.P.	APPLIED RESEARCH	4
DRAWING No.		PROJECT No. 40.018-001 (38)	PITTSBURGH, PA.	
ARL 1-1278		DATE 6-29-64		

ATLAS LITHO CO PGH PA 1028 CLEARPRINT

Plate thickness, inches	1/4	3/8	1/2
Predicted minimum r_I, inches	0.4	0.7	0.9
Actual r_I, inches			
Specimens A	0.19 (cracked)	0.23 (cracked)	0.75 (cracked)
B	0.34 (not cracked)	0.53 (not cracked)	0.78 (cracked)
C	0.42 (not cracked)	0.72 (not cracked)	0.94 (not cracked)

Typical Specimens for Each Plate Thickness



Specimen A - smooth surface - cracked

Specimen C - smooth surface - not cracked

Specimen A - as-rolled surface - cracked

Figure 5. Verification of predicted cold-forming limits of various-thickness plates of 5Ni-Cr-Mo-V steel.

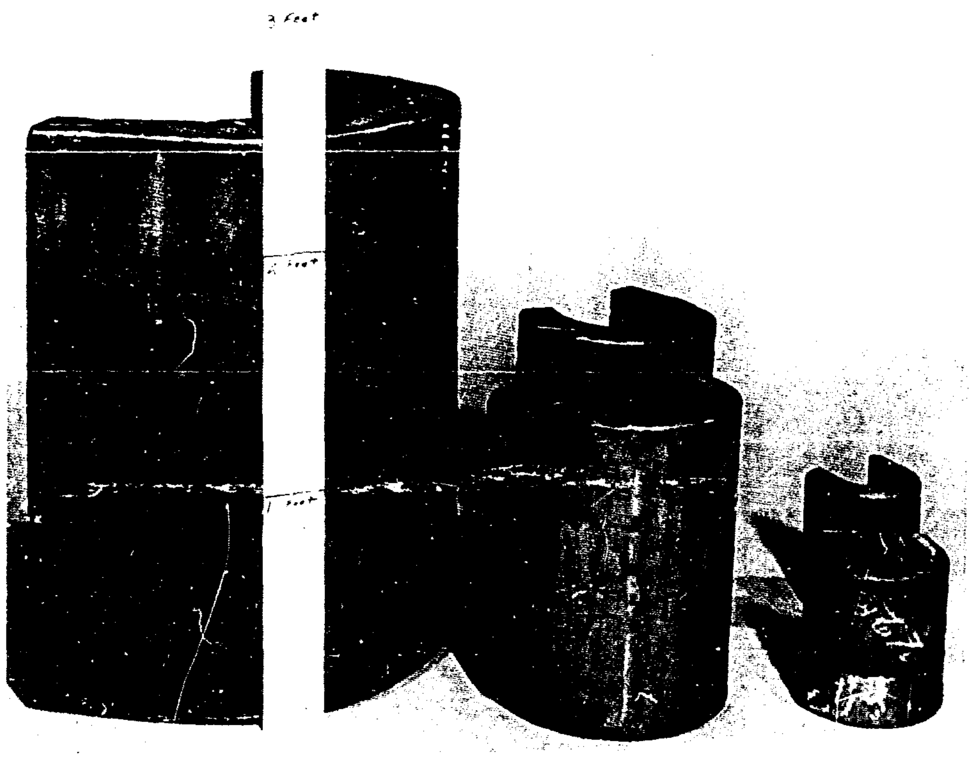
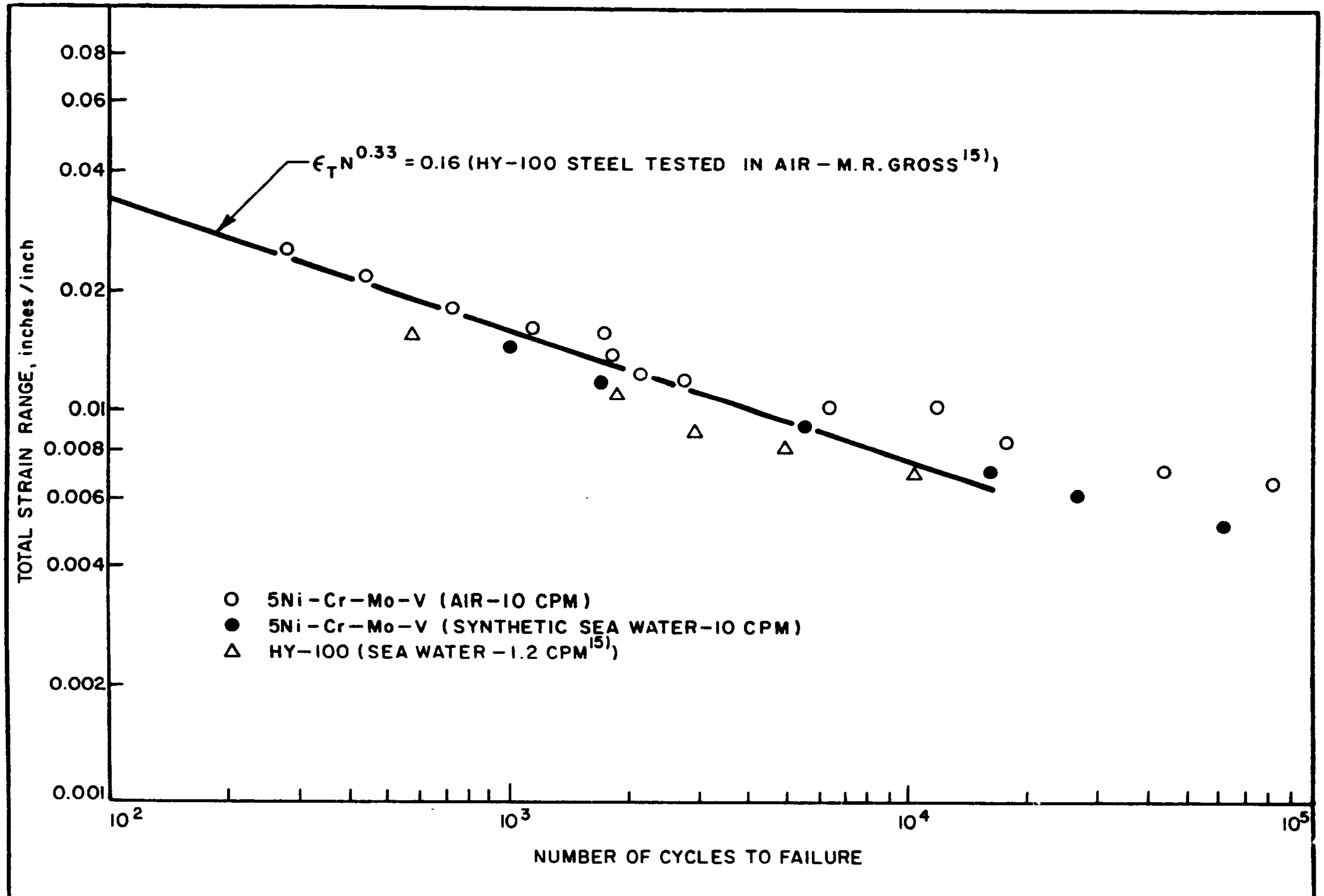


Figure 6. 5Ni-Cr-Mo-V plates 1, 2, and 3-3/8 inches thick cold-formed to minimum predicted bend radii.



LOW-CYCLE CORROSION FATIGUE RESULTS FOR HY-100 AND 5Ni-Cr-Mo-V STEELS

DRAWN BY	CHK'D BY	APPROVED BY	UNITED STATES STEEL CORPORATION	FIGURE NO.
G.A.Z.	S.T.R.	J.H.G.	APPLIED RESEARCH	7
DRAWING No		PROJECT No 40.018-001 (38)	PITTSBURGH, PA.	
ARL 18-480		DATE 11-12-64		

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